TELEPRESENCE CONTROL OF MOBILE ROBOTS: KILAUEA MARSOKHOD EXPERIMENT

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ABSTRACT

Mobile robots will be a key requirement for future exploration of Mars. Mobility will be required to achieve the goals of the Mars Surveyor program and will be critical for science operations on Mars during future human missions. We describe here a field experiment to simulate science operations of a planetary surface rover on Mars and on the Moon. The Marsokhod planetary surface rover was deployed on Kilauea Volcano HI in February 1995 and operated via satellite communications from NASA Ames Research Center. Simulations of teleoperated rover missions on Mars and on the Moon were performed for three days each. During the simulations, science teams analyzed data from the Marsokhod and deduced the geologic setting and history of the field site. In the Mars simulation, the rover traversed 800 m of terrain, made observations at 8 science stations, and obtained several hundred images. We estimate that performing the same operation on Mars would require about 30 days. In the Lunar simulation, the rover was operated in real time with a continuous stereo video image transmission, and traversed 1.2 km in 15 hours of operation. The experiments show that mobile robots can be used to successfully perform field geology on other planets. We argue that rovers are needed for the Surveyor program to Mars which can traverse >10 km during a mission duration of one year. This capability could be achieved by cooperating with the Russians and using the Marsokhod rover.

1. INTRODUCTION

Efficient and low cost operation of mobile robots will be a key requirement for the future exploration of Mars. Telepresent control of mobile robots may well prove to be an enabling technology for answering the most compelling scientific questions about Mars and will also be critical for scientific operations during future human missions.

The Mars Surveyor program, the United States Mars exploration program planned for the coming decade, has three main objectives: to search for evidence of past or present life on Mars, to determine the climate history of the planet, and to understand the state and distribution of resources useful for future human settlement of Mars. To achieve these objectives, it will be necessary to have mobility to gain access to terrains of interest and especially to access the solid rock record on Mars. Stationary landers are able to sample only soil and atmospheric properties. For example, Viking was unable to perform measurements on any rocks even though there were plenty of rocks in the vicinity of the lander. Soil and atmosphere properties do not vary from place to place on Mars, and actually represent a cumulative average of the history of conditions. Thus, it will not be possible to reconstruct events in the history of Mars from the properties of the soil and atmosphere. Conversely, rocks contain the record of the instant in time that they were formed. Thus, studying the rock record yields a look into history, and studying sequences of rocks and their relationships can allow the reconstruction of a historic record[1].

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Climate:
The key to understanding whether life ever evolved on Mars and what was its eventual fate is to reconstruct the history of the Martian climate. The geologic evidence suggests that liquid water flowed on early Mars and this has led to the belief that early Mars was warm and wet compared to present conditions[2]. However, it has not been possible to determine how warm, how wet, or how long these conditions may have lasted. It remains controversial whether Mars every sustained an active hydrological cycle involving precipitation and open standing bodies of liquid water. To answer these questions, we will need to visit sites where sediments laid down in ancient lake beds can be studied. Structures of interest for *in situ* observations are likely to be very localized and may be too small to be seen from orbital observations. Mobility will be needed to provide access to such structures and observations and must be made at spatial scales of millimeters to meters. In other words, the capabilities of a field geologist must be duplicated in robotic spacecraft. Clearly, the key capabilities are the robotic equivalent of eyes, hands, and feet.

Life:
Did life evolve on Mars and leave a fossil record? The preponderance of evidence suggests that, if life ever evolved on Mars, that event would have occurred at least 3 billion years ago when conditions were more clement than at present[2]. As Mars became cooler and drier, life is likely to have been pushed into marginal ecological niches or possibly become extinct. Life originated on Earth and was widespread within 500 million years after the formation of a solid surface on the planet. So, by 3 billion years ago, there is a fossil record of life on Earth. However, that record was left by single-celled microbes which dominated Earth for most of its history. In fact, multicellular life on Earth has only existed for the last 600 million years. It is multicellular life forms that leave the preponderance of fossils on Earth (from hard shells and bones). Extrapolating the terrestrial record to Mars would suggest that life on Mars had insufficient time to develop multicellular forms. The duration of early clement conditions on Mars is not known but estimates range from .5 to 2 billion years with the latter number representing a strong upper limit and a long period of gradual decline. Therefor, it is highly likely that any fossil record found on Mars will be from bacterial life.

Precambrian fossil bacteria on Earth are found in layered sedimentary structures called stromatolites which consist of microscopic layers of carbonate minerals encasing entombed bacteria. While these forms can be quite large (up to tens of meters in size) they must be closely examined to determine a biogenic origin. Searching for a fossil record will require the ability to perform a thorough search of a site that has the greatest likelihood to have preserved fossils. Lake beds and hydrothermal springs are the most likely sites to search, but finding evidence of fossil life will require a great deal of searching around in such a site.

Requirements for finding evidence of fossil life on Mars include the ability to target a high priority site based on orbital data, an ability to land accurately within that site, and the ability to perform a thorough and detailed search of the site. Mobile robots are really the only technology that has the capabilities needed to meet these requirements.

2. FIELD EXPERIMENTS WITH MOBILE ROBOTS

We have performed a series of field experiments with mobile robots in Mars analog environments. Two types of field experiments have been performed: 1) Underwater experiments using a submersible remotely operated vehicle with real-time telepresent control. This control. This vehicle was used to study aqueous environments thought to be good analogs of liquid water environments present on ancient Mars. 2) Mars mission simulations using the Marsokhod planetary surface rover. These mission simulations were designed to develop a science operations strategy for performing remote scientific exploration using mobile robots. Experiments with the TROV have been described by Hine and others[3] and Stoker and others[4]. In the following section, we will describe a mission simulation using the Marsokhod planetary surface rover. Additional information about the mission can be obtained on the world wide web at "http://maas-neotek.arc.nasa.gov:80/marsokhod".

2.1. Marsokhod Mars and Moon Mission Simulations

Two mission simulations have been performed using the Marsokhod surface rover in the past two years. The first mission simulation was performed in Amboy CA from March 29-31, 1994. The second was performed on Kilauea volcano, Hawaii from February 20-26, 1995. The Amboy experiment is described by Greeley and others[5]. Here, we will focus on the Kilauea field experiment.

The Kilauea experiment simulated a mission to Mars and to the Moon operated from Earth. We tried to simulate actual mission conditions as closely as possible, given the time constraints of the field test.

The goal of the Kilauea experiment was to determine the mobility requirements and the operational strategy for using Marsokhod to answer detailed scientific questions in a relevant analog field site. The key objective was to determine the requirements and "desirements" for doing field geology using a mobile robot.

The Southwest Desert region of the Kilauea volcano park in Hawaii was chosen for the field site. This site, which has experienced repeated volcanic eruptions, and is almost devoid of vegetation, offers terrain which is a good Mars analog from the viewpoint of both appearance and the geological processes represented there. In a relatively small area one can visit features caused by pyroclastic eruptions, lava flows, ash flows, aeolian processes, and fluvial processes. Fracture zones caused by local faulting offer natural exposures of cross-sections through sequences of landforms created by these processes. The area also is a good geological analog to volcanic terrain on the Moon.

2.2 Marsokhod Capabilities

Figure 1 shows the Marsokhod rover on Kilauea. The Marsokhod rover is the culmination of over two decades of research and development by various groups within the Russian space community. It draws its heritage from the Lunokhod vehicles, which are to date the only remotely operated rovers to be deployed on another planetary surface. The vehicle is essentially a six-wheel drive skid-steer chassis composed of three two-wheel segments. These segments are joined to each other via a passive roll articulation, and the front and back segments can pitch relative to each other. This three degree-of-freedom articulation allows the chassis to conform to extremely large obstacles.

In addition to these passive articulations, there are two actuated articulations at the front and rear of the vehicle which allow it to extend and retract the end wheel segments. This "swimming" motion allows the rover to change its wheel base to improve turning efficiency, as well as climb up extremely tall obstacles or soft slopes.

The wheels of the Marsokhod are basically hollow titanium shells with aluminum and titanium structural members, and titanium fins to increase traction. Each wheel is actuated by a brushed DC motor via a five-stage planetary gearhead, giving an overall reduction of 625:1. The only portion of the wheel axle which rotates is the final stage of the gearhead; this provides a fixed mounting point for internal payload, and avoids the use of slip rings.

The large volume and low height of the wheels make them ideal for housing the vehicle's on-board power storage. Six NiCd battery packs are carried, one in each wheel, providing the rover with about four hours of power with the current instrument suite; proposed space missions utilize RTG's housed in the wheels to power the vehicle as well as to heat it. Servo-amplifiers for the wheel motors are also housed inside the wheels.

The primary goal of the Kilauea mission was geological science. To perform this mission, the Marsokhod was outfitted with an array of low, medium, and high resolution cameras, as well as a four degree of freedom manipulator arm to position cameras and excavate soil. The rover is also equipped with a magnetometer/inclinometer unit for heading and attitude feedback, and digital and analog communications links for digital telemetry and real-time video. The manipulator arm, with a microscopic-focus wrist camera, and a forward-looking high-resolution digital camera are mounted on the front payload pallet. A mast is mounted on the middle pallet to provide elevation for either a pan-tilt stereo pair (Lunar mission simulation) or a fixed forward looking stereo pair (Mars mission simulation). The magnetometer and radio link antennas are mounted on the mast as well. The after pallet contains the rover's power electronics, video electronics, radios, and on-board computer. The all-up weight of the rover was approximately 150 kg, with 55 kg going to batteries, 40 kg going to the rover chassis, and 10 kg going to the arm, and the remainder to electronics.

Figure 1. Marsokhod Rover at the Kilauea Volcano field site.

The rover is equipped with a VME-based on-board computer which handles all on-board computing functions. The computer's main responsibilities are servo-control of the wheel and manipulator motors, dead-reckoning and heading control of the vehicle using compass feedback, pan-tilt control, and control of the rover's four on-board cameras. The computer is also responsible for periodically broadcasting its state (position, orientation, health) to the operations centers. The main CPU is a 68030/68882 VME board running the VxWorks real-time OS. Motor control of the vehicle's six wheels and four-joint arm is done using dedicated motor control boards; control of the pan-tilt head is achieved with a dedicated micro-controller via serial communications. The computer is equipped with a video digitizer to capture still images for digital retransmission, and an analog/digital I/O board to measure bus voltages, passive articulation sensors, and motor currents; this board is also used to turn various subsystems on and off via relays.

The communications system for the Kilauea field operations consisted of short-range radio links to a satellite uplink, where real-time compressed video and data were multiplexed together onto a single T1 satellite channel. The channel was downlinked to a ground station in Texas, and the circuit to Ames Research Center was completed via land fiber. The rover's digital data link was over 900 MHz spread-spectrum radio ethernet bridge, providing 200 kb/sec of bandwidth, while a single color video channel was operated over a 1.2 GHz link. The field site in Hawaii was connected directly to the Internet, allowing remote operation not only by the science team, but by various individuals located around the country and around the world.

Marsokhod was operated remotely from NASA Ames Research Center in Mountain View, California. The remote operations equipment and software is described by Hine and others[3]. The time delay due to the satellite and ground data links was measured to be approximately 1.0 seconds round trip. This was an adequate simulation of the communications time-delay from the Earth to the Moon, so we did not introduce added delay. Since we had only 3 days in which to do the Mars mission simulation, we elected not to introduce added time-delay here as well.

The user interface for controlling Marsokhod used the Virtual Environment Vehicle Interface (VEVI)[3] running on a Silicon Graphics workstation. Moving the rover was literally a push button operation. A graphical button panel, linked to settings of direction, speed, and time, was used to drive the rover. Other buttons on the panel were pushed to collect and transmit digital image frames.

The camera configuration for the Mars mission was designed to simulate the Mars Together Marsokhod mission configuration. This mission was planned for a 1998 launch but has subsequently been delayed and is now under consideration for a 2001 launch. Stereo cameras were mounted on a fixed mast at a horizontal spacing of 1 m and a height of 1.5 m. These were color video cameras but individual digital frames were selected using a frame grabber. Color was stripped and images were transmitted in black and white. Navigation images were compressed to quarter frame before transmission. Science images obtained at the behest of the science team were transmitted without compression.

The Lunar mission payload simulated that planned for the Pele mission--a lunar rover mission proposed to the Discovery program. The operator interface for the Lunar mission was essentially the same as for the Mars mission except that color stereo video was transmitted so that the Marsokhod could be operated in real time. For the Lunar mission, the stereo cameras were mounted on a pan and tilt camera platform at 1.5 m height and at horizontal spacing simulating human interocular distance.

The Mars and Lunar mission simulations were performed for three days each. The science strategy for the Mars mission simulation was developed by Professor Ron Greeley (Arizona State University) and for the Lunar mission simulation by Professor Jeff Taylor (University of Hawaii).

2.3 Mars Mission Description

The Mars mission simulation was performed using two science teams who were not allowed to communicate with each other. Team 1 had access for planning purposes to a set of simulated orbital and descent images. Team 2 had simulated orbital images only. Both teams were presented with a set of scientific questions about the site and Team 1 designed a traverse to answer these questions using the simulated descent images. This traverse planning took several iterations to accomplish because the initial places chosen by the science team were subsequently eliminated for operational reasons. Operational issues included the frequent rainfall and environmental concerns since Kilauea is in a national park and is subject to stringent environmental protection. Furthermore, there was not a good basis *a priori* to estimate the time required to perform specific tasks and therefor Team 1 initially underestimated the time requirements. For these reasons, Team 1 had to remain flexible and rapidly replan their traverses when operational problems arose, and was forced to drop some of their study targets during each traverse to move on to higher priority targets. Even though the operational issues encountered are different than those that would occur on Mars, flexibility and rapid planning and decision making will be crucial to the success of rover missions on other planets.

Team 1 was responsible for directing the rover traverses and data acquisition at each science station. Team members were assigned roles which included: mission commander, science scribe, and data analyst. The mission commander had responsibility for working closely with the rover operator to direct the traverses, and to request images of particular features and other tasks to be performed at each station. The science scribe kept detailed notes on the science operation, including what was being done and the time requirements for specific tasks. Other team members focused on analysis of the images as they came in. Team 1 rotated task assignments between team members so that each member could get a better idea of the different job requirements.

Rover operations separated into two categories: (1) traversing terrain and (2) obtaining data at science stations. Traverses were designed to get the rover from one science station to the next. During a traverse between stations, only low resolution navigation images were obtained. However, on several occasions a navigation image turned up something unexpected which required further investigation before moving on. Thus, some unplanned science stations were added to the schedule as we went along.

Team 2 worked in a more passive mode and analyzed the images as they were received. They were hampered by not having support imaging of sufficient resolution to allow them to locate exactly where each rover image was obtained. Thus, they were not able to determine the broader geologic context of each rover image.

2.4 Mars Mission Results

In all, during the Mars operation the Marsokhod traversed 800 m over a period of 18 hours of rover operation. Science observations were performed at 8 stops and a total of a few hundred navigation frames were obtained.

Team 1 developed a geologic model of the site and determined from stratigraphic relations the sequence of events. Subsequent ground truth walk through of the field site showed that their observations and geologic interpretation were generally correct. However the lack of color made distinguishing some different geological units impossible which resulted in some incorrect interpretations. In addition, a few important features quite near the traverse area were missed altogether.

Team 1 found that the efficiency of conducting scientific interpretations improved with each successive day, emphasizing the importance of using analog simulations for team training prior to actual rover missions.

Team 2 found that they were unable to develop a geologic context for their observations or to locate the images received on the simulated satellite images they were provided. Thus, while they were able to interpret the images they obtained for geologic information, they were not able to develop a correct geologic model for the region and they did not attempt to determine stratigraphic relations of units observed.

The Mars team made several recommendations for imaging, emphasizing the importance of high quality imaging for geologic interpretations.

• Descent imaging is critical for planning traverses and for understanding the geologic context of the data received. Even if descent imaging is obtained, extended rover operations will eventually leave the local area of the descent images. Therefor orbital support imaging of the highest possible resolution, preferably 1m or less, is critical for rover missions.

• Color imaging is essential: Stereo images were black and white and this proved very inhibitory to separating out different composition geologic units and resulted in some mistaken interpretations. Multispectral imaging, such as that planned for the Mars Pathfinder mission, is highly desirable and should be evaluated in a future field test.

• Pan and tilt capability on the primary camera would be very useful. Not having it results in a much longer time spent obtaining a desired image view because the entire Rover must be moved and pointed in the right direction. The pointing angle of a camera is very difficult to control by moving the rover. The team estimated that not having pan and tilt increased the number of command cycles required to obtain a desired image by a factor of 5 or more

3.4 Lunar Mission Description

The Lunar mission simulation involved real-time stereo television observations which were supplemented by stereo digital images from the same cameras (obtained by grabbing and transmitting stereo frames) and high resolution digital images from the camera mounted on the arm. The digital high resolution body mounted camera was not used during the Lunar mission.

The Lunar mission operations were conducted at Ames research center. A shift commander, located at Ames, was responsible for making decisions on where to move, images to capture, and whether to deploy the arm and other instruments. The shift commander was supported by science team members at Ames who analyzed data and provided advice as to where to go and what to do next. In addition to the Ames team, there was a science team located at NASA Johnson Space Center who received the data simultaneously with the Ames team and were in continuous communication with them via a conference telephone line. The involvement of the distributed team worked dramatically well and group discussions of the geology were very productive.

2.5 Lunar Simulation Results

Figure 2 shows an example of the traverse path for the Lunar and Mars missions. The Marsokhod was operated in Lunar mode for 15 hours, and traversed a total distance of 1.2 km in that mode.

Figure 2. Aerial photograph of field area showing Lunar traverse for first day's operation (white dots) and Mars traverse for two days operation (black dots).

The Lunar team produced a geologic map of the area traversed, using the aerial photographs as a base, along with descriptions and age relations of the major geologic units. The team identified the key features of the geology of the traverse area, demonstrating that sound geologic observations can be made telerobotically. The quality of the observations increased each day, reflecting the importance of team experience in conducting this type of mission. The team members were all experienced field geologists and that was essential for performing the remote observations with the rover.

The Lunar team found that the data came in faster than they could analyze it which led to leaving some sites before it was optimal to do so. The Lunar team at Ames was quite small (4 scientists). It is essential to have enough scientists involved making observations, analyzing images, planning the traverses based on the images, and observing during the traverse. The team concluded that 6-9 geologists would be required to be involved during each operational shift.

Team structure and assignments recommended by the Lunar team include:
1. Shift Commander (1 person): Makes the decisions about the details of the traverse, when to move on, images to be taken and other analysis to be made. The Commander spends most of the time getting input for decisions from the Rover operator and the Chief Analyst. Traverse planning and making decisions about data took most of the Shift Commander's attention.

2. Image Logger (1 person): Keeps track of the images taken and annotates them with the proper geologic context. Also serves as an assistant to Shift Commander.

3. Chief Analyst (1 person): Serves as the link between the team of analysts and the Commander. Person must synthesize the observations and interpretations made by the analysts and communicate them to the Mission Commander. The commanders decisions are based in large part on the input from the Chief Analyst.

4. Analysts (at least 3): Team of geologists that look carefully at the images, make photomosaics and do preliminary image processing. The data come so fast that it would be optimal to use at least two teams for this purpose, both communicating with the Chief Analyst. The test indicated that at least two geologists need to work together on related images with a third taking notes.

One major problem identified by the Lunar team leader (Jeff Taylor, personal communication) was that the team was object-oriented. As a consequence, several important features were missed while the team was pressing on to achieve preplanned objectives. Due to time pressure, the Rover was never operated in an exploratory mode. A similar conclusion was reached by the Mars team after a personal visit to the field site. We conclude that rover observations, while substantially better than achievable through stationary landers, are not as good as those made by a field geologist who has a greater ability to look around and notice unexpected things.

3. CONCLUSIONS AND RECOMMENDATIONS

The most important lesson learned from this experiment is the value of mobility in obtaining access to the geologic record.

There are two requirements for mobility on Mars:

• Mobility needed to get to a field site of interest;
• Mobility needed to investigate a field site of interest.

The mobility needed to reach the field site is set by the targeting accuracy of the surface lander. A field site of interest typically will be a few square kilometers in size while the landing ellipse for present generation entry vehicles (blunt vehicles lacking active control) is typically quite large -- order 100 km across. Even in cases where the entire landing area is of high interest, the most compelling features (those that drove the landing site selection) may still be quite distant from the actual landing site -- thus mobility of the same scale as the landing error is needed to reach those features. In summary, with present entry systems the required mobility to get to the field site of interest is of order 100 km.

The second requirement is mobility within the site of interest. At a given site it is not necessary to visit every feature, but some must be investigated in detail. For example, features representative of several different kinds of geologic processes should be visited.

The Kilauea experiment was performed at a site having rich scientific diversity within a small area -- comparable to Martian cases -- so our experience has allowed us to draw some conclusions about the kind of mobility that will be needed once a Mars rover reaches its target site. On Kilauea, several features separated by 10-100 meters were examined intensively during each day of operation. These features generally represented one type of geologic process, for example volcanic processes. Obtaining the desired data about each feature required a few meters of mobility. Features representing another type of process (for example, fluvial erosion) were also present in the same general area, but further away. A typical traverse to get to information about another interesting process would be in the range 0.5-5 km.

Based on all of the factors and experience discussed above, we can identify four relevant scales of mobility:

1. The mobility needed to get from the landing area to a field site of general interest (order 100 km).
2. The mobility needed to get around within a field site of interest to reach different landforms produced by specific kinds of geologic processes (order 10 km).
3. The mobility needed to get relevant measurements in the vicinity of these features -- involving a series of "stops", each localized but separate (10's meters to 1 km).
4. The mobility needed to perform observations at an actual stop to obtain the desired data (1-5 meters).

3.1 Recommendations for Surveyor

Based on the experience gained from these experiments, we can make recommendations for the strategy required to achieve the goals of the Mars surveyor program.

First, sites must be identified based on orbital data that have high probability for providing information about the history of water, climate, and life on Mars. For example, an interesting kind of site would be a paleolake basin in the ancient cratered terrain. The site should have compelling geologic evidence for having sustained liquid water conditions over a long period of time during the period when warm wet conditions existed on Mars (most likely to have been during the Noachian epoch). It would be best if the lake deposited sediments were exposed by a stream cut or excavated by a crater formed by a meteor impact. One site which matches this description is Gusev crater, which is currently being evaluated as a candidate landing site [Gulick, private communication].

A capable rover should be landed at the site with landing accuracy sufficient to guarantee that the field site or sites of interest can be accessed from the landing site within the mobility range of the rover.

Once the rover has reached the field site, a traverse should be performed to answer detailed science questions about the site. It should be possible to pose and test specific hypotheses about the processes responsible for formation of various geologic features. Rover traverses should be designed to obtain the most science in the least time and distance traversed, rather than to traverse the most distance. Mission operations must remain flexible to changing plans based on serendipitous discovery. The rapidity with which the team must respond, and the flexibility of the operations, argues for small science teams and streamlined processes be in place for achieving team decisions.

Experience shows that traversing from science target to science target requires relatively few command cycles in reasonably simple terrain as compared to studying a science target. One can anticipate rovers which are able to navigate autonomously from target to target without detailed ground commands, although that has not been demonstrated in any actual rover trails to date. However, data obtained at any science target will involve a high degree of interaction and decision making on the part of a science team so that observations can best be tailored to suit science needs.

Based on the Kilauea field test, we estimate that rover traverses of 1 km, including 10 detailed science target stops, should be possible in each month of operation. Therefor, rover missions with a baseline duration of 1 year can provide the range of mobility desired to achieve the goals of the Surveyor program. By collaborating with the Russians and using the Marsokhod rover, the Surveyor Program could have this capability in time for a 2001 launch.

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